On Scalability and Interference Avoidance in Nonlinear Adjacent Channel Interference Networks

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Abstract—Adjacent channel interference caused by intermodulation distortion adversely affects the network operations in next generation heterogeneous and dynamic spectrum access networks. Multitudes of radio access technologies make the receivers susceptible to harmful interference due to nonlinear RF front ends. In this paper we analyze the intermodulation distortion arising from pairwise interactions of adjacent channel signals from a spectrum centric point of view and develop frameworks to ascertain the adjacent channel signals causing interference at a given desired channel. We further propose achievable schemes for interference avoidance and assess the scalability of the next generation Nonlinear Adjacent Channel Interference Networks. We further propose schemes for complete interference protection of incumbents with sensitive receiver requirements from secondary operations in adjacent channels in the spatio-temporal vicinity. This paper presents valuable insights on scalability and schemes for nonlinear adjacent channel interference avoidance in next generation shared spectrum networks.

I. INTRODUCTION

Wireless spectrum is a scarce natural resource and maximizing its utilization is of at most importance to meet the ever increasing demands in data rate and bandwidth. Spectrum Sharing and Dynamic Spectrum Access (DSA) have been identified as key technologies to make efficient use of the spectrum [1] – [5]. With new spectrum opening up for sharing [6], [7], diverse Radio Access Technologies (RAT) and allied services will access the same spectrum band in the future.

Diversity in RAT will introduce diversity in the RF front ends and device types. This gives rise to a unique set of challenges, which are otherwise not encountered in operations of traditional planned spectrum allocation. Shared access to radio spectrum makes the receivers vulnerable to harmful interference. Much of the existing research concentrates on dealing with co-channel interference and the vulnerability of receivers to harmful interference arising due to signals from adjacent channels has been largely ignored in the literature.

Adjacent channel interference primarily results due to the nonlinear transfer characteristics exhibited by receiver RF Front Ends. The effects of front end nonlinearity are multifold [8]. In this paper, we focus on one such effect known as ‘Intermodulation Distortion’ due to interactions of two adjacent channel signals that enter the receiver chain. Importance of considering adjacent channel interference arising due to receiver imperfections in resource allocation was highlighted in [10]. Channel assignments accounting for intermodulation distortions based on the individual receiver characteristics of the nodes in a network was previously addressed in [11], [12]. These works concentrated on maximizing the sum rate through efficient channel allocation so as to minimize the impact of nonlinear adjacent channel interference. However, the more fundamental questions regarding the scalability of such networks through network level interference avoidance remain unanswered in the literature. The next generation wireless networks in heterogeneous and dynamic spectrum environments whose operations are constrained by the nonlinear interference emanating from signals on adjacent channels are termed in this paper as Nonlinear Adjacent Channel Interference Networks (NACIN).

In order to understand the interactions of signals on adjacent channels and their impact at a given desired channel, in this paper we present a model specific analysis of the spectrum redistribution of the input signal to the RF front end as it traverses through the RF chain. Such a framework will help in adjacent channel co-existence analysis and also aid in a network level management of interference. Further, using this framework we propose an achievable scheme for nonlinear adjacent channel interference avoidance to study and assess the scalability of such networks. The proposed scheme also gives valuable insights for channel assignments and wireless network design through nonlinear interference avoidance.

The analysis carried out in this paper renders a systematic methodology for the protection of incumbent operations with highly sensitive receivers. The radio-astronomy receivers, Fixed Satellite System Earth Stations, GPS receivers, and many more operations require a high receiver sensitivity to capture the weak desired signals. Thus, such incumbent operations have to be protected from the detriments caused due to adjacent channel interference arising from intermodulation distortions. Ensuring complete interference protection for such incumbent operations is critical for the successful deployment of secondary systems for opportunistic access even on adjacent channels in the spatio-temporal vicinity of such primary systems. We use the analysis presented in this paper to develop achievable schemes to ensure the complete protection of channels occupied by sensitive incumbents from any nonlinear adjacent channel interference. The outcome of this demonstrates that there exists schemes for protection from secondary interference due to nonlinear adjacent channel interference, with the absence of any exclusion zone. Such an assurance for incumbents will potentially pave way for an easier transition of more licensed bands to open up for opportunistic access to increase the overall spectrum utilization.

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The main contributions of this paper are:

- Introduce the concept of Nonlinear Adjacent Channel Interference Networks (NACIN) encountered in next generation heterogeneous and dynamic spectrum access networks
- Analyze the interactions of signals adjacent channels causing nonlinear interference at a given desired channel and extend this to baseband modulated symbols
- Propose achievable schemes for interference avoidance in NACINs to assess the operational scalability of such networks
- Propose achievable schemes for protection of sensitive incumbents from nonlinear interference due to intermodulation distortion arising due to secondary operations in adjacent channels

The remainder of this paper is organized as follows: Section II introduces the nonlinear receiver model and the resulting distortions; Section III introduces the Nonlinear Adjacent Channel Interference Networks; Section IV carries out analysis to identify all the adjacent channels producing two-tone intermodulation interference at a given desired channel and extends this to baseband modulated symbols; Section V introduces interference avoidance in NACINs for a 3 × 3 network; Section VI generalizes and presents an achievable scheme for interference avoidance to assess the scalability of NACINs; Section VII details the achievable schemes for the protection of incumbent operations with high receiver sensitivity; and finally Section VIII concludes the paper.

II. NONLINEAR RECEIVER MODEL

We consider a memoryless polynomial receiver front end model with input-output relation described by [8], [9],

\[ R(t) = \alpha_1 Z(t) + \alpha_2 Z^2(t) + \alpha_3 Z^3(t) + \alpha_4 Z^4(t) + \ldots \]  

(1)

where \( Z(t) \) is the input, \( R(t) \) is the output, \( \alpha_i \)'s are the coefficients for \( i \)th order terms, and \( \alpha_1 \) is the linear gain of the RF chain. The even order terms produce harmonics outside the desired band, which can easily be filtered out, while the odd order terms on the contrary produce intermodulation terms within the desired band [8], [9]. The third order term contributes significantly larger to the in-band intermodulation distortion products than the other odd order harmonics. Thus, a third order approximation gives a good estimate of the non-linearity for receivers. To quantify the extent of non-linearity, standard procedure is to extend the third order and the fundamental curves on the transfer characteristics plot of powers on the decibel scale, so that they intersect. The point of intersection is known as Third order Intercept point or IIP₂ [8], [9], [13] (or Intermodulation Intercept Point). It can be shown that,

\[ \text{IIP}_3 = \sqrt{\frac{4}{3}} \left( \frac{\alpha_1}{\alpha_3} \right) \]  

(8), [9]. Throughout the discussion, we assume a linear gain, \( \alpha_1 = 1 \). Thus, we have \( \alpha_3 = \left( \frac{4}{3} \text{IIP}_3 \right) \) in terms of IIP₃.

Note that this IIP₃ denotes the nonlinearity for entire receiver front end chain. This can be computed easily by cascade modeling of the nonlinearity of each receiver component or stage [8], [9].

When subjected to a two tone input of the form, \( Z(t) = A_1 \cos(\omega_1 t) + A_2 \cos(\omega_2 t) \), the several terms that feature in the output, \( R(t) \) are: (1) The first order term produces outputs at \( \omega_1 \) and \( \omega_2 \). (2) The second order term produces outputs at DC, \( \omega_1 - \omega_2 \) and \( \omega_1 + \omega_2 \). (3) The third order term produces outputs at DC, the fundamental frequencies \( (\omega_1, \omega_2) \), third order harmonics \( (3\omega_1, 3\omega_2) \), and certain new frequencies at \( 2\omega_1 + \omega_2, \omega_1 + 2\omega_2, 2\omega_1 - \omega_2 \) and \( 2\omega_2 - \omega_1 \). We thus observe that, \( 2\omega_1 - \omega_2 \) and \( 2\omega_2 - \omega_1 \) fall in the region of operation of the device, while others can be further filtered out. (5) The fourth order term generates outputs at DC, \( 2\omega_1, 2\omega_2, 4\omega_1, 4\omega_2, \omega_1 \pm \omega_2, \omega_1 \pm 2\omega_2, 3\omega_1 \pm \omega_2 \) and \( 3\omega_2 \pm \omega_1 \) and so on.

In general, we can easily deduce that the two tone input generates distortions at various frequencies surrounding the harmonics of both the input signals. At a given harmonic, the frequencies produced are spaced at \( \Delta \omega = | \omega_1 - \omega_2 | \). We can thus generalize the spurious frequencies to be present at \( \omega_{out} = | \pm p\omega_1 \pm q\omega_2 | \) where \( p \) and \( q \) assume positive integer values. Upon expanding the terms, we also find that the power of the intermodulation signals decreases as the polynomial order increases.

III. NONLINEAR ADJACENT CHANNEL INTERFERENCE NETWORK (NACIN)

Consider a network of \( N \) transmitters and \( N \) receivers with diverse Radio Access Technologies (RAT) communicating over \( N \) equal and distinct band limited channels (or frequency bins) over a shared spectrum band. The receiver pre-selector filters span all the \( N \) channels, and thus receive signals in channels adjacent to the desired signal. Due to the nonlinearity of the receiver front ends, each receiver encounters interference due to the signals entering the RF chain in the adjacent channels. Unlike co-channel interference, this adjacent channel interference is nonlinear function of the signals, as shown in Fig. 1 and this network is termed Nonlinear Adjacent Channel Interference Network (NACIN). Combating such nonlinear interference is challenging due to the following reasons: (1) Interfering signals are present on adjacent channels and hence will require additional degrees of freedom in the receiver architecture, (2) The nonlinear structure of the interference increases the computational complexity, and (3) Due to the
multi-RAT operating in a shared spectrum network, as opposed to traditional homogeneous networks.

The fundamental network capacity of such a network is an open problem. Further, it also depends on the receiver model and characterization used in describing the nonlinear structure of the interference. As mentioned in the previous section, in this paper, we assume the third order polynomial nonlinearity for receivers and proceed towards analyzing the limits of such a network. Since interference cancellation in such networks is a hard problem, network capacity is dictated by the number of interference-free symbols that can be recovered by ‘avoiding’ the interference.

IV. INTERMODULATION DISTORTION AND ADJACENT SYMBOL INTERFERENCE

In this section, we analyze the structure of two-tone intermodulation interference emanating from adjacent frequency bins.

Lemma 1. Two signals at frequency bins j and k respectively, \( j, k \in [1, N] \) produce third order intermodulation products at a frequency bin \( n \in [1, N] \); \( n \neq j, n \neq k \), if the condition, \(| j - k | = \min\{|n - j|, |n - k|\} \) is satisfied.

Proof: Omitted for brevity. See [14].

Lemma 2. The second order multiplicative term of the intermodulation product of two signals at bins j and k respectively produced at bin n, is produced by the signal in the bin \( n \pm \min\{|n - j|; |n - k|\} \in \{j, k\}; \forall j, k, n \in [1, N] \).

Proof: Omitted for brevity. See [14]. Based on these properties, it is possible to characterize the adjacent channel frequency bins producing two-tone intermodulation products at a desired frequency bin n.

Theorem 1. \( \Psi_n \) is the set of all ordered pairs \((j, k)\); \( \forall j, k \in [1, N] \); \( j \neq k, j \neq n \) of adjacent channel frequency bins that produce intermodulation products at a given frequency bin n, where,

\[
\Psi_n = \left\{ \left( n - 2 \left\lfloor \frac{n - 1}{2} \right\rfloor, n - \left\lfloor \frac{n - 1}{2} \right\rfloor \right), \ldots, \left( n - 2, n - 1 \right), \left( n + 1, n + 2 \right), \ldots, \left( n + \left\lfloor \frac{N - n}{2} \right\rfloor, n + 2 \left\lfloor \frac{N - n}{2} \right\rfloor \right) \right\}
\]

(2)

Proof: Omitted for brevity. See [14].

We now analyze how the modulated IQ samples interfere with the desired symbol. The modulated signal is given by,

\[
Z(t) = X(t) \cos(2\pi f_c t) - jY(t) \sin(2\pi f_c t)
\]

(3)

where \( X(t) \) and \( Y(t) \) are the in-phase and quadrature components of the baseband signal of bandwidth \( B < f_c \). The angular frequency, \( \omega_c = 2\pi f_c \). The signal \( \tilde{Z}(t) = X(t) + jY(t) \) is the complex envelope of \( Z(t) \), which is the complex baseband signal with bandwidth \( B \).

Consider three frequencies, equally spaced and adjacent to each other in the same band, at \( \omega_1, \omega_2, \) and \( \omega_3 \) with \( \omega_1 < \omega_2 < \omega_3 \). Since they are equally spaced, \(|\omega_1 - \omega_2| = |\omega_2 - \omega_3|\), \(2\omega_2 - \omega_3 = \omega_1\), and \(2\omega_2 - \omega_1 = \omega_3\) hold true. Without loss of generality, we assume \( \omega_1 \) as the desired frequency and the other two are adjacent channel interfering signals. We examine the interference resulting due to the intermodulation products of \( \omega_2 \) and \( \omega_3 \) on the frequency \( \omega_1 \) using the complex IQ signal representations. We note that several works [8], [9] have deduced the interaction between signals of adjacent channels and the intermodulation product. We extend those works here to analyze the interaction of complex IQ baseband modulated symbols on adjacent channels and the resulting nonlinear interference. The two interferers are represented as,

\[
\begin{align*}
Z_2 &= X_2 \cos(\omega_2) - jY_2 \sin(\omega_2) \\
Z_3 &= X_3 \cos(\omega_3) - jY_3 \sin(\omega_3)
\end{align*}
\]

(4)

Note that the time index \( t \) is omitted for convenience. The receiver model is given by, \( R = \alpha_1 Z + \alpha_3 Z^3 \) where \( Z = Z_2 + Z_3 \).

Lemma 3. The received complex baseband symbol \( \tilde{R}_1 \) at the frequency \( \omega_1 \) is given by,

\[
\tilde{R}_1 = \tilde{Z}_1 + \frac{3}{4} \alpha_3 \tilde{Z}_2^2 \tilde{Z}_3
\]

(5)

where \( \tilde{Z}_k = X_k + jY_k \), the complex baseband symbol (envelope) of the signal. Thus, generalizing for \( N \) signals, the received symbol model is given by,

\[
\tilde{R}_n = \tilde{Z}_n + \frac{3}{4} \alpha_3 \sum_{\forall (j, k) \in \Psi_n} \tilde{Z}_j \tilde{Z}_k
\]

(6)

where \( \Psi_n \) is a set of all ordered pairs \((j, k); i, j \in [1, N] \) given by equation (2) of Theorem 1 and \( \alpha_3 \) is the third-order co-efficient of the receiver in frequency bin n.

Proof: Omitted for brevity. See [14]. The term \( \frac{3}{4} \alpha_3 \sum_{\forall (j, k) \in \Psi} \tilde{Z}_j \tilde{Z}_k \) represents the interference emanating from baseband complex modulated symbols of the adjacent channels and hence is termed Adjacent Symbol Interference (ASI).

V. INTERFERENCE AVOIDANCE IN A 3 \times 3 NACIN

Consider a \( 3 \times 3 \) NACIN as shown in the left panel of Fig. 2. The nodes are transmitting simultaneously on three equal and band limited channels centered around \( f_1, f_2 \) and \( f_3 \). Due to RF front end nonlinearity on the receivers, they encounter pairwise intermodulation interference from symbols on adjacent channels. As explained in the previous sections, the structure of this adjacent symbol interference is nonlinear, and specifically for a \( 3 \times 3 \) network, the interfering terms for each receiver is as shown in the Left panel Fig. 2. Symbols \( Z_2 \) and \( Z_3 \) interact to cause interference at \( Rx_1 \), and symbols \( Z_1 \) and \( Z_2 \) interact to cause interference at \( Rx_3 \), the interactions between the symbols is different. Further, \( Rx_2 \) does not face any pairwise intermodulation interference, and receives interference-free desired symbol. Using the analysis presented in the previous section, we formalize these observations and proceed to outlay a scheme to exploit the structure of interfering symbols for interference avoidance.

From Theorem 1 we see that for \( N = 3 \), the set of interfering frequency bins as \( \Psi_1 = \{(2, 3)\}; \Psi_2 = \phi; \Psi_3 = \{(1, 2)\}, \)
where \(\phi\) represents a null set. Accordingly, the Tx-Rx pair using the frequency bin (or channel) \(n = 2\) does not face any ASI. In the ensuing discussion we assume that presence of any interfering term results in the loss of the desired symbol. As stated before, interference cancellation is a tough problem for NACINs operating in shared spectrum spaces. While we acknowledge that in practice it depends on the power of the interference, for the purpose of evaluating network performance limits it is necessary to make this assumption. Besides, this assumption represents the worst case scenario designing schemes for total interference protection for primary shared spectrum spaces.

As seen from the Left panel in Fig. 2, one symbol on \(n = 2\) is successfully decoded per transmission period in a \(3 \times 3\) NACIN. Consequently we see that nulling one transmitter per transmission period following a round-robin mechanism could be carried out and such a scheme yields two successfully decoded symbols per transmission on this \(3 \times 3\) network, as shown in the Right panel of Fig. 2. Thus, exploiting the interference structure, 6 symbols can be decoded in 3 transmission periods and a DoF = 2 is achievable for such a network.

VI. ACHIEVABLE SCHEME FOR INTERFERENCE AVOIDANCE IN A \(N \times N\) NACIN

In this section, we examine the \(N \times N\) NACIN and develop an achievable scheme for interference avoidance through channel nulling.

A. Definitions and Notations

We now define an indexing function \(x_n\), which denotes whether the frequency bin \(n\) is active or nulled as,

\[
x_n = \begin{cases} 
1 & \text{if bin } n \text{ active} \\
0 & \text{if bin } n \text{ nulled}
\end{cases}
\]  

(7)

We denote the set of all ordered pairs causing ASI over the NACIN as the union of all \(\Psi_n\) in equation (2),

\[
\Psi = \bigcup_{n \in [1, N]} \Psi_n
\]  

(8)

So long as \(\Psi \neq \phi\) (null set), there exists ASI on at least one link in the NACIN.

We define an operation \(\Xi(\ast)\) on a set of ordered pairs, as the ordered multiset of the union of all singletons formed by the set of the ordered pairs on which it is operated upon. Essentially, if \(G = \{(a_1, b_1), (a_2, b_2), \ldots, (a_N, b_N)\}\) is a set of ordered pairs, then \(\Xi(G) = \{a_1, b_1, a_2, b_2, \ldots, a_N, b_N\}\).

Let \(\Theta_n = \Xi(\Psi_n)\) denote the ordered set of all frequency bins (with repetition) causing ASI at bin \(n\) as obtained from taking the union of all singletons formed from \(\Psi_n\). Let \(\lambda_n^k = \sum_{\Theta_n} k \delta_{\theta_n^k}\), where \(\theta_n^k\) is the \(k^{th}\) element of the ordered set \(\Theta_n\) and \(\delta_{\theta_n^k}\) is the Kronecker delta function, denote the number of occurrences of frequency bin \(k \neq n\) in the set \(\Theta_n\). Let \(s = [s_1, s_2, \ldots, s_N]^T\) be a \(N\times1\) vector whose \(n^{th}\) row denotes the number of ASI terms contributed by the frequency bin \(n\). It is obtained as, \(s_n = \sum_k \lambda_n^k\) denote the number of ASI terms contributed by the \(n^{th}\) active link.

B. Problem Formulation

Using the definitions and notations described, we now proceed toward a formal description of the problem. The objective is to maximize the number of active channels in the NACIN, while ensuring none of the Tx-Rx pairs on those active channels encounter ASI. In other words, the question asked is, what is the least number of channels that need to be nulled so that none of the active channels suffer any ASI? Thus, the problem is formulated as,

\[
\mathcal{S} = \max \sum_{n=1}^{N} x_n \\
\text{s.t. } \Psi = \phi
\]  

(9)

This is a combinatorial problem of choosing \(M \in [1, N]\) nodes to maximize a given metric, with an important added complexity where the cost of choosing a node can be ascertained only with the knowledge of all the \(M\) nodes chosen. This represents a complicated version of knapsack and thus is NP hard.

C. Achievable Scheme

In this section we propose an achievable scheme for the formulated problem. The intuition behind this scheme is to
The scheme is formalized Algorithm 1. ASI terms until the active channels are free from any ASI.

**Algorithm 1** Achievable Scheme for NACIN

1. **INITIALIZE**: \( T = [1, N] \). Set of all active channel
2. **INITIALIZE**: \( \Psi = \bigcup_{n \in T} \Psi_n \).
3. **INITIALIZE**: \( \Theta_n = \Xi(\Psi_n) \ \forall n \in T \).
4. **INITIALIZE**: \( \lambda_k^n = \sum_{j=1}^{r} \delta_{\phi_k j} \ \forall k, n \in T \).
5. **INITIALIZE**: \( s_n = \sum_{k} \lambda_k^n, \ \forall k, n \in T \).

**while** \( \Psi \neq \emptyset \)

6. \( n^* = \arg \max_{n} \{s_n\} \ \forall n \in T \).
7. \( [s]_{n^*} = 0 \).
8. \( \Psi_n = \Psi_n \setminus \{(j, k)\} \) if \( j = n^* \) or \( k = n^* \).
9. \( \Psi = \Psi \setminus \Psi_{n^*} \).
10. \( T = T \setminus n^* \).
11. \( \Theta_n = \Xi(\Psi_n) \ \forall n \in T \).
12. \( \lambda_k^n = \sum_{j=1}^{r} \delta_{\phi_k j} \ \forall k, n \in T \).
13. \( s_n = \sum_{k} \lambda_k^n, \ \forall k, n \in T \).
14. **while** \( \Psi \neq \emptyset \).

sequentially null the channel which contributes to maximum ASI terms until the active channels are free from any ASI. The scheme is formalized Algorithm 1.

The behavior of the achievable scheme with number of Tx-Rx pairs (channels) is as shown in Fig. 3. We note that this is just an achievable scheme and the optimality or approximation bounds are beyond the scope of this paper and left for future work. We also note that for this analysis we have considered interference to be binary. Practical systems can accept non-zero interference while maintaining a certain assured quality of service. Development of algorithms and achievable schemes with interference thresholds is future work.

**VII. PROTECTION OF INCUMBENT WITH SENSITIVE RECEIVERS**

Next generation shared spectrum will include incumbents with highly sensitive receivers. Examples include radio-astronomy receivers, fixed satellite system earth stations, GPS receivers, etc. These receivers will not only have to be protected from co-channel interference, but also from adjacent channel interference. We use the notations and definitions introduced in the previous section.

**A. Problem Formulation**

We present two variants of the problem. The primary objective in both is to ensure the complete protection of the incumbent with sensitive receiver. In the first variant we assume even the secondary receivers cannot accept any adjacent channel interference due to two-tone intermodulation and in the second we assume that the secondary receivers are immune to adjacent channel interference (and hence, primary protections is the only objective).

Let there be \( N \) channels and the incumbent be located at any arbitrary channel denoted by \( \ell \in [1, N] \). The problem is to accommodate as many secondary operations as possible in bands adjacent to the incumbent such that it does not cause any interference to the incumbent.

**Case 1: With Secondary Protection**

\[
J = \max_{n=1}^{N} x_n \quad (11)
\]

\[
\text{s.t. } \Psi_\ell = \phi; \ \Psi = \emptyset \quad (12)
\]

**Case 2: No Secondary Protection**

\[
J = \max_{n=1}^{N} x_n \quad (13)
\]

\[
\text{s.t. } \Psi_\ell = \phi \quad (14)
\]

**B. Achievable Schemes for Incumbent Protection**

In this section we propose two achievable schemes for incumbent protection for the two cases presented in the previous section. Channels which produce the maximum interference at bin \( n = \ell \) are sequentially nulled until \( \Psi_\ell = \phi \) and \( \Psi \neq \emptyset \) for Case 1 as detailed in Algorithm 2. For Case 2, we are only concerned about the incumbent protection, and hence the channels are nulled only to satisfy the condition \( \Psi_\ell = \phi \) as detailed in Algorithm 3.

The behavior of the achievable schemes is shown in Fig. 4. The implication of this analysis is that even extremely sensitive incumbent receivers can be protected from interference emanating from intermodulation distortion due to receiver nonlinearity. Thus, theoretically, secondary operations in channels adjacent to sensitive incumbents is possible even with no geographical exclusion zones if the network is engineered to satisfy the constraints of interference protection. This instills the much needed confidence to the incumbent operations with sensitive receivers to open the spectrum for sharing in next generation wireless networks, thus improving the overall spectrum utilization.

**VIII. CONCLUSIONS**

This paper introduces the Nonlinear Adjacent Channel Interference Networks (NACIN) encountered due two-tone intermodulation distortions arising due to receiver nonlinearity in next generation heterogeneous and shared spectrum networks. Achievable schemes for interference avoidance to analyze the limits of such networks were proposed, and schemes to protect incumbent operations from interference were detailed. The
Algorithm 2 Incumbent Protection with Secondary Protection
1: INITIALIZE: \( \mathcal{T} = [1, N] \). Set of all active channels
2: INITIALIZE: \( \mathcal{N} = \bigcup_{n \in \mathcal{T}} \mathcal{N}_n \).
3: INITIALIZE: \( \Theta_n = \mathcal{N}(\Psi_n) \forall n \in \mathcal{T} \)
4: INITIALIZE: \( \lambda_k^n = \sum_{j=1}^{\Theta_n} \delta_{\Theta_j} k \), \( \forall k, n \in \mathcal{T} \)
5: INITIALIZE: \( s : s_n = \sum_k \lambda_k^n, \forall k, n \in \mathcal{T} \)
6: do
7: \( \Psi \neq \phi \) do
8: \( k^* = \arg \max_k \lambda_k^n \)
9: \( \{s\}_k^n = 0 \)
10: \( \Psi = \Psi \setminus \{(j, k)\} \) if \( j = k^* \) or \( k = k^* \);
11: \( \forall (j, k) \in \Psi \)
12: \( \mathcal{Y} = \mathcal{Y} \setminus \Psi_k^* \)
13: \( \Theta_n = \mathcal{N}(\Psi) \forall n \in \mathcal{T} \)
14: \( \lambda_k^n = \sum_{j=1}^{\Theta_n} \delta_{\Theta_j} k \), \( \forall k, n \in \mathcal{T} \)
15: Update \( s : s_n = \sum_k \lambda_k^n, \forall k, n \in \mathcal{T} \)
end while
17: \( n^* = \arg \max_n |s| \forall n \in \mathcal{T} \)
18: \( |s|_n^{*} = 0 \)
19: \( \Psi = \Psi \setminus \{(j, k)\} \) if \( j = n^* \) or \( k = n^* \);
20: \( \forall (j, k) \in \Psi_n, \forall n \in \mathcal{T} \)
21: \( \mathcal{T} = \mathcal{T} \setminus n^* \)
22: \( \Theta_n = \mathcal{N}(\Psi) \forall n \in \mathcal{T} \)
23: \( \lambda_k^n = \sum_{j=1}^{\Theta_n} \delta_{\Theta_j} k \), \( \forall k, n \in \mathcal{T} \)
24: Update \( s : s_n = \sum_k \lambda_k^n, \forall k, n \in \mathcal{T} \)
25: while \( \mathcal{Y} \neq \phi \)

Algorithm 3 Incumbent Protection with No Secondary Protection
1: INITIALIZE: \( \mathcal{T} = [1, N] \). Set of all active channels
2: INITIALIZE: \( \Theta_n = \mathcal{N}(\Psi) \forall n \in \mathcal{T} \)
3: INITIALIZE: \( \lambda_k^n = \sum_{j=1}^{\Theta_n} \delta_{\Theta_j} k \), \( \forall k, n \in \mathcal{T} \)
4: do
5: \( k^* = \arg \max_k \lambda_k^n \)
6: \( |s|_k^n = 0 \)
7: \( \Psi = \Psi \setminus \{(j, k)\} \) if \( j = k^* \) or \( k = k^* \);
8: \( \forall (j, k) \in \Psi \)
9: \( \mathcal{T} = \mathcal{T} \setminus k^* \)
10: \( \lambda_k^n = \sum_{j=1}^{\Theta_n} \delta_{\Theta_j} k \), \( \forall k \in \mathcal{T} \)
end while

operational scalability of the network devoid of nonlinear adjacent channel interference across the active channels assuming a third order polynomial approximation for the receivers was found to be a sub-linear function of the number of channels available for the proposed achievable scheme. Further, it was shown that secondary operations in adjacent channels ensuring complete protection from nonlinear adjacent channel interference for incumbent operations with sensitive receivers was possible with no exclusion zones. Interference avoidance schemes to enable such operations were proposed. With a nuance that allows secondary users to accept adjacent channel interference, it was shown that the scalability of the network with complete incumbent protection was almost a linear function of the available channels for the proposed achievable schemes. The analysis in this paper and the proposed schemes provide an assessment for the scalability of NACINs and also render a systematic approach for interference avoidance in next generation heterogeneous and Multi-RAT network design.

REFERENCES